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16. ABSTRACT The report gives results of a study of the collection of charged submicron sized particles by fiber beds. Removal efficiency was determined as a function of particle resistivity, fiber bed resistivity, superficial gas velocity, and total concentration of the aerosol. Using a 12-in. thick polypropylene fiber bed, greater than 90% removal efficiency was reported for superficial bed velocities up to 300 ft/min. For a 6-in. bed, 90% removal was possible up to 200 ft/min. In both cases, the pressure drops for these systems were low (less than 1 in. H2O). A third bed was tested, comprised of a 6-in. Teflon fiber bed followed immediately by a 6-in. polypropylene bed. This composite 12-in. bed did not perform as well as the homogeneous 12-in. bed. In all tests, the most important parameter was bed face velocity. In general, the collection efficiency of the fiber bed decreased linearly with increasing velocity.

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ELECTROSTATIC CAPTURE OF FINE PARTICLES IN FIBER BEDS

by

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ABSTRACT

The emission of submicron sized particles is the most difficult to effectively control with current state-of-the-art technology. Experiments at Battelle-Northwest led to the discovery that charged particles could be efficiently captured by a thick fiber bed having a high bed-volume to fiber-volume ratio and a very low pressure drop. Interim results are presented for the removal efficiency as a function of particle resistivity, superficial gas velocity, bed depth and aerosol concentration. In general, for bed pressure drops less than 0.5 in H_2O efficiencies greater than 90 percent were obtained at 300 ft/min face velocity over the particle size range of 0.06 - 0.7 μm AMD and a particle resistivity range of 10^8 - 10^{12} ohm-cm. The most important variable was the bed face velocity with the collection efficiency varying inversely with velocity. The bed depth and volume void fraction were other significant variables bearing on the efficiency of the system.

Emperical equations indicate a 100 percent collection efficiency might be attainable near or somewhat below a bed face velocity of 50 ft/min. However, a more sensitive measurement method would be required for experimental confirmation.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of co-workers D. A. Nelson for conducting the tests, D. L. Lessor for discussions on the mathematical modeling of the phenomenon, and the technical guidance and suggestions of J. A. Abbott and D. C. Drehmel of the Environmental Protection Agency.

SUMMARY AND CONCLUSIONS

The efficient removal of charged submicron particles from flowing gas streams with a bed consisting of fibers having a high dielectric constant was demonstrated experimentally. Although not all of the facets of operation for optimization of the concept have been explored in detail, the tests conducted to date suggest many practical applications for relatively economical particle control not attainable with presently available concepts. Based on mass measurements, the emperical equations developed from the data collected to date indicate that a 100 percent collection efficiency at some face velocity below 50 ft/min might be attainable but would be extremely difficult to prove experimentally. Other observations from the information accumulated to date were as follows:

1. Velocity was the prime variable with respect to efficiency. For the 6 in. thick bed, the efficiency decreased linearly with increasing velocity up to about 200 ft/min bed face velocity. The minimal data beyond this velocity are suspect and need redefinition. For the 12 in. thick bed the linear relationship existed up to the highest flow rate tested of 320 ft/min. Both produced efficiencies above 90 percent at the above-stated flow rates for the submicron particles used.

2. Bed thickness apparently had a pronounced effect on collection efficiency. However, bed thickness and fiber volume density are dependent variables as evidenced by the compressed 3 in. bed which showed a higher efficiency than the 6 in. bed having a slightly higher void fraction. Although not directly comparable due to void fraction differences the 12 in. filter showed about a 10 and 2 percent higher efficiency than the 6 in. bed at 300 and 100 ft/min face velocity. This difference in the slope of the curves suggests a deeper penetration with increasing velocity which appears reasonable providing all other conditions are equal. Thus the ratio of the efficiencies should increase with velocity for equivalent particle characteristics.

3. Particle Size. Although not a prime variable, there was no detectable influence on efficiency over the range tested -- ~0.06 to 0.83 μm AMD. The stated AMD's are thought to be high due to the uncertainty of extrapolation from about 90 to 50 percent of the log normal plot.

4. Pad Resistivity. There was no discernable difference between polypropylene or teflon fibers with respect to efficiency and apparent field charge strength and shape. The principal criteria for a fiber are that it be electrically non-conducting and have a significantly larger diameter than the submicron particles. A 6 in. thick stainless steel demister pad produced very low collection efficiencies -- somewhat higher than that expected for image force collection.

5. Particle Resistivity. The majority of the data indicated there was no significant trend in collection efficiency over the range of approximately 10^8 - 10^{12} ohm-cm particle resistivity. Since one test series showed a slightly lower efficiency for the 10^8 ohm-cm NH_4Cl and the model suggests that efficiency should decrease with decreasing particle resistivity, particles with a much lower resistivity should be studied to better describe any differences and establish the lower boundary limit, if one exists.

6. Dust Concentrations. Particle concentrations ranging from 10 to 250 mg/M^3 were used without any significant differences except for the apparent higher field charge for the higher concentrations. Since measurement reproducibility increased and length of test time varied inversely with concentration, most of the new wind tunnel tests were made between 50 - 100 mg/M^3 dust loading.

7. Particle Charge Level. The fraction of uncharged particles challenging the filter is apparently more pertinent to the success of the concept than the charge level of the particles at least if near saturation charge is obtained. As would be expected, the bed had no affinity for uncharged particles at the higher velocities and showed about 8 percent retention at 50 ft/min. The instrumentation used was not sensitive enough to provide the refinement required to accurately define the fraction of uncharged particles downstream of the charge section. Consequently, valid information is not available on

the ratio of charged to uncharged particles reaching the filters. However, the efficiencies obtained indicate that the uncharged particles must have been a very small fraction of the total particle load. Faraday cage measurements indicated both near and supersaturation charge of the particles. The variability of the data is believed to be a function of the measurement of small currents in the presence of relatively high electrical fields and very little credence is given to the data.

8. Humidity. No attempts were made to study humidity of the aerosol as a variable. The maximum relative humidity observed during the experiments was 50 percent and generally hovered between 30-40 percent. Consequently, no effects generally applicable to humidity were discernable. For one test series with Na_2O particles, room humidity in excess of 45 percent produced a liquid NaOH deposit in the charge section and fiber bed resulting in degraded particle charging and bed efficiency. The principal cause for the loss in collection efficiency, particle charging or bed penetration or a combination of both was indeterminant. Evidence of shorting in the charge section as well as a lower field charge suggests that inadequate particle charging might have been the predominant factor.

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INTRODUCTION

The cost/benefit ratio for the control of particulate emissions has increased significantly with the decreasing control limits and for the more resistant submicron particulates there is a large imbalance which will probably increase as attention becomes focused on the submicron species once the "boulders" are under control. Consequently, there is a great need for control technology that will meet the atmospheric disposal limits and yet have a marked influence on lowering both the capital investment and operating expense. It is recognized by all that as the particle resistivity increases and the size decreases, the efficiency of the electrostatic precipitator (ESP) is significantly degraded. The trend to burn Western low sulfur coal to reduce the sulfur emission has initiated a large effort in gas-particle conditioning in an effort to offset the ESP loss of efficiency due to the higher particle resistivity. Present-day mechanical devices control the "rocks" reasonably well but are found wanting for the smaller submicron particulates. Bag filters are the most effective present technology for filtration of submicron particulates, but have a very significant drawback in the limited face velocity and high pressure drop. Consequently, for high volume discharge gases the filter area required is extremely large producing high capital and operating costs. The problem initiated a myriad of research programs aimed at improving or developing a system or device to meet the emission standards and somewhat secondarily for more economically controlling emissions. A significant portion of the work was oriented toward the use of electrical charges or electrical properties for enhancement of filtration efficiencies. The novel concept described utilizes the electrostatic properties of particles and fibers of high dielectric strength to effectively remove submicron and other particulates from waste or process gas streams.

BACKGROUND

During the course of experiments based on charged water spray-droplet scrubbing, it was discovered that a dry demister pad of a non-conducting fiber was acting as an effective filter for submicron particulates of unipolar charge and produced significantly greater efficiencies than observed for the charged particle-charged spray drop tests. This observation, by A. K. Postma and W. K. Winegardner,* initiated a few confirmatory tests that reduced the phenomenon to practice and led to an Environmental Protection Agency (EPA)** grant to explore the boundary conditions of the variables thought to be of importance. Funding was later obtained from the Battelle Energy Program office (BEP) for a phase of the work specifically directed toward fly ash and for continued mathematical modeling of the observed phenomenon which will be issued in a separate report. At this point in time, a logical equation-of-state has been developed by D. L. Lessor but an equation providing apriori predictions is not yet completed.

Availability and cost of a new system dictated the use of the spray-drop system for the initial parametric tests. The variability of the data and unexplained observations highlighted the inadequacies of the system for the more refined tests addressing parametric boundary conditions. However, the data were sufficiently encouraging to warrant a new wind tunnel that would provide a unidirectional, constant velocity flow between the principal sampling points. This discussion of interim information relates, principally, to the experimental data obtained with the new wind tunnel and addresses only the interim experimental tests assigned to the EPA grant program.

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* Patent pending.

** Work performed under EPA Grant No. R-801581-02-2.

METHODS OF APPROACH

The collection mechanism involves the deposition of charged particles by self-induced electric fields within a bed of electrically non-conducting fibers. Since the electrical field in the bed is induced by molecular ion or charged particle deposition, efficient operation of the system depends on the development of electrical fields of the same polarity sufficient to overcome the coulombic repulsion of the fiber within times smaller than the residence time of the particle within the bed. From this criteria, the following variables might be expected to play an important role:

Particle Size -	influences mobility
Air Velocity -	residence time of particles in the vicinity of a fiber
Pad Resistivity -	charge leakage rate and field strengths and distribution
Pad Thickness -	target area residence time
Dust Surface Coverage -	flow geometry, charge leakage rate
Particle Resistivity -	charge leakage for continuous coating and particle charge level
Charge Level of Particles -	mobility of particles in field
Total Charge Interception Rate -	maximum field in bed due to particle deposition
Fiber Density -	mean free path between particle and fiber-localized residence time
Humidity -	influence on bed conductivity for hygroscopic particles

A complete block experimental plan involving the ten parameters listed would require more than a practical number of tests for proof of the concept. Therefore the program was designed to explore ranges of most of the variables listed. The boundary conditions of the parameters to be explored include the following:

Particle Size - not to be considered a prime variable. All tests will involve submicron particles near the 0.1 to 0.3 μm size range, which corresponds to minimum mobility and maximum challenge to the system. The removal efficiency would be expected to be higher for particles above 1 μm.

Air Velocity - to be varied from 50 to 400 ft/min superficial bed velocity.

Pad Resistivity - Available demisters of stainless steel, polypropylene and teflon will be used. The stainless steel will show the effect of pad conductivity. Teflon fibers would allow operation at temperatures near 300°F and should be examined for application.

Pad Thickness - Thickness of 3, 6 and 12 inch beds will be tested for comparative efficiencies.

Particle Resistivity - Highly important, generation of particles having resistivities of 10^7, 10^9, 10^{11} ohm-cm will be sought -- the highest resistivity reflecting a severe challenge to electrostatic precipitators.

Particle Charge Level - not considered as a primary parameter for study at this time. Saturation or near saturation charge appears advantageous and the charger will be operated at a voltage to produce same.

Dust Loading - Particle concentrations will be varied from 10 to 100 milligrams per cubic meter.

The data for each experiment included the removal efficiency, pressure drop, relative humidity, air flow rate, and dust loading. The particle size and particle resistivity was determined for each generating condition thought to alter these characteristic properties of the particle. The electrical properties of the bed, e.g. field charge level, would be dependent primarily on charge deposition and leakage rate through some finite resistance for the ungrounded bed. Consequently, some indication of the relative field charge level and distribution within the bed was obtained during "steady state" conditions by inference from current measurements. These measurements were considered as important input for support of a mathematical model and possibly desirable for scaleup with a design engineering model.

WIND TUNNEL SCHEMATIC

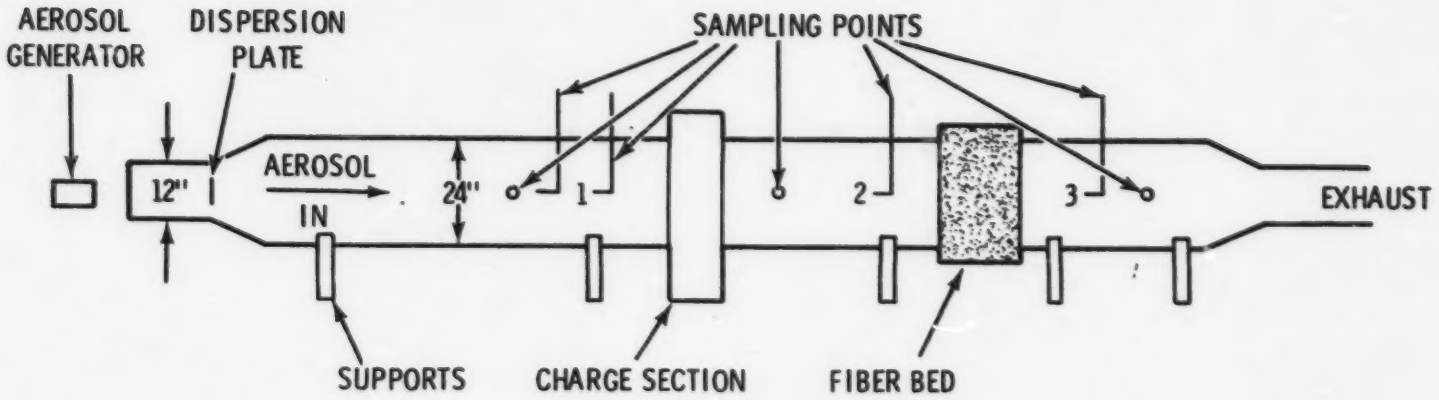

FIGURE 1. Wind Tunnel Schematic

EXPERIMENTAL EQUIPMENT

The initial investigation of the observed phenomenon was conducted in the available charged spray-drop test apparatus which experimentally left much to be desired for the more definitive parametric study attempting to define the influencing variables and the related boundary conditions. A new wind tunnel system was designed to provide a unidirectional uniform velocity from particle generation point to the last downstream sampling point.

TEST SYSTEM

Figure 1 is a schematic drawing of the system which consists of a 7 foot long 24 inch diameter pipe, a short corona charging section with an effective cross-sectional charging area equal to that of the duct, a 3 foot long section between the charger and fiber bed to preclude any direct field charge effects from the charge section, and a bed frame for the knitted fiber mats. The inlets and outlets to the bed were 24* inches diameter. The bed dimension was made 28 inches by 28 inches to extend the experimental run time before edge leakage became the predominant source of downstream particles. The frame was made with lucite and was electrically isolated from the rest of the system as was the charging section. The system was built in sections for future alteration of configurations and distances between principal components and was held together with electrically insulated external straps. A dispersion plate was placed in the 12 inch diameter inlet at the transition point to produce the required uniform velocity profile at the three principal sampling points at positions 1, 2 and 3.

CORONA CHARGING SECTION

The charging section of the system, shown schematically in Figure 2, was designed for rather easy alteration of the electrode-to-ground spacing to vary the particle deposition on the ground rods. Half-inch diameter rods rather than plates were used for the ground in an effort to reduce deposition, to minimize the sparkover rate late in the runs and to extend run time without particle charging degradation. The last electrode wire

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* Although EPA policy requires the use of metric units in all its publications, non-metric units are used in this report for simplicity and clarity. Readers more familiar with the metric system units are asked to use the conversion factors on page 32 .

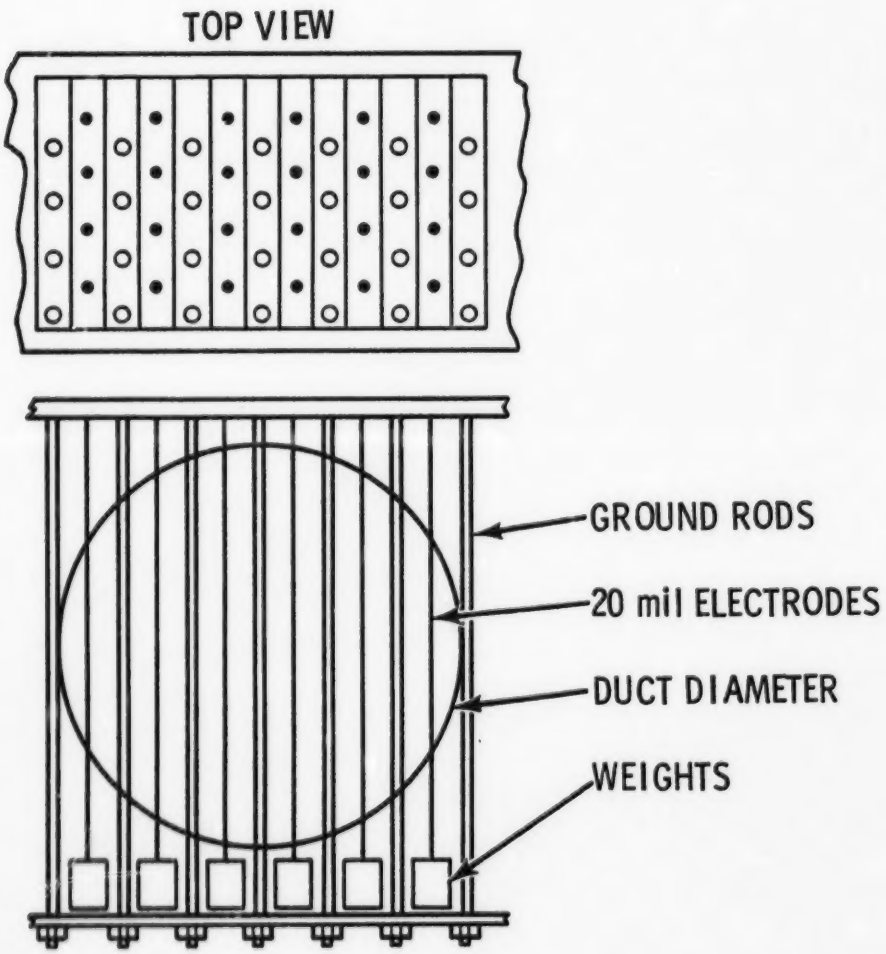


FIGURE 2. Schematic Charge Section Without Can

was placed downstream of the last rod in an effort to charge any reentrained uncharged particles arising from the ground rods. Whether or not this was effective has not yet been determined since repairs to the measuring instrumentation could not be made prior to the end of the test series. However, it is doubtful any small differences could have been determined under the high particle loads of 10^9 - 10^{12} part/M^3 due to instrument sensitivity. The voltage to the electrodes was applied through 30 meg-ohm resistors which acted as electrical chokes limiting the current to any one electrode under sparkover conditions or under a direct short to ground preventing degrading of corona from the other electrodes. This electrical choke tended to reduce the sparkover late in the run and increase run time. The effective field depth of about 6 in. gave a particle residence time of about 100 milliseconds at 300 ft/min face velocity -- more than adequate to reach near saturation charge.

FIBER BED SECTION

The frame holding the fiber bed was made of 1/2 inch thick lucite for visibility and for its high dielectric properties. The bed surface area extended 2 inches beyond the duct diameter to eliminate early edge leakage along the framing where the fiber density is at a minimum as was observed in experiments using the spray-drop test system. This apparently delayed leakage until a significant load had accumulated on the front face and the increase in the pressure drop diverted some particles to the region of a lower pressure drop. From visual observation this edge leakage, which was accentuated by the support wires, appeared to lower the efficiencies for some of the last tests in a run series just prior to bed cleaning. The observed "frame" leakage is strictly a function of the experimental bed construction and could be designed out of a bed made specifically for electrostatic filtration. Also, under industrial applications the bed would normally be cleaned before the pressure drop increased sufficiently to alter the flow pattern and increase the velocity through a much smaller bed fraction.

The bed was supported within the frame by a teflon coated wire grid with about a 4 inch wire spacing (Figure 3). The used demister pads were disassembled and the individual knitted mats layered into the supporting

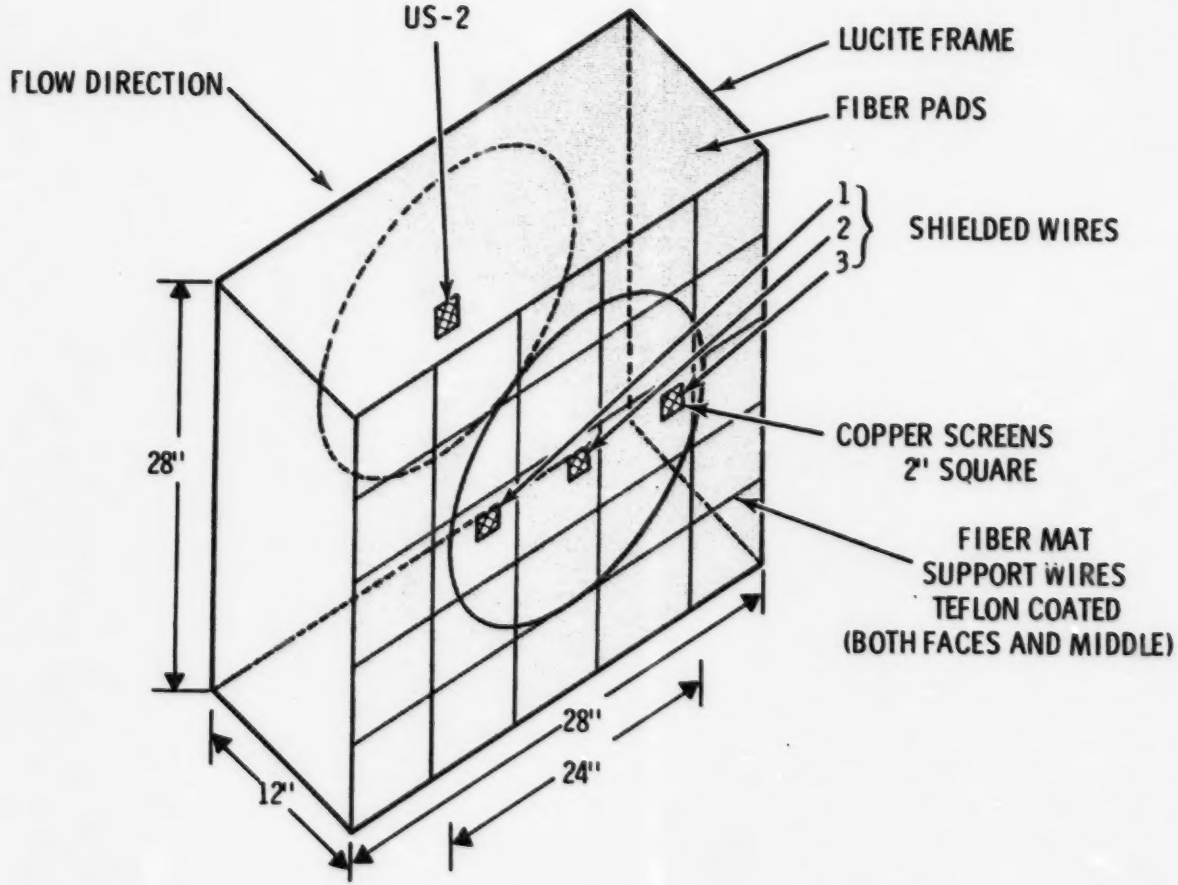


FIGURE 3. Fiber Bed Schematic

frame. Since the maximum width of the mats was about 14 inches, alternate layers were juxtapositioned at 90° angles to each other to preclude gaps or any major lower density regions that might "short circuit" the bed. This method of forming the bed also provided a means for varying the void volume fraction -- that space unoccupied by fibers.

EXPERIMENTAL CONDITIONS

FIBER BED VOID FRACTION

The void fraction of the fiber bed was defined as that volume of the bed not occupied by the fiber volume and was determined from the bulk weight of the fiber mats, density of the fiber per unit length and the fiber diameter.

For this series of tests the 6 inch bed was packed to a void fraction (VF) of ∿0.96. For the 12 inch bed, the flow direction of the frame was reversed and the first 6 inches then packed to a VF of ∿0.975. The lower fiber density was used in the first 6 inches to increase particle penetration depth and increase the load to bed pressure drop ratio. The lower density in the first 6 inches accomplished both goals, but appeared to be detrimental with respect to efficiencies in the later stages of a continuous run series and to the length of operating time before breakthrough. This was true particularly for MgO which normally showed a greater penetration depth than NH_4Cl or Na_2O. Breakthrough of the bed is defined as the appearance of agglomerates on the sample downstream from the fiber bed which were not observed in the previous samples. A conducting copper wire surrounded the fiber bed and small screens (Figure 3) were placed on the front and back faces to intermittently measure the current to ground as an indication of the bed electrical conditions during operation.

PARTICLE GENERATION AND CHARACTERISTICS

Three particles were used in this series of experiments to highlight any change in efficiency with particle resistivity -- namely ammonium chloride, magnesium oxide and sodium oxide. The NH_4Cl particle was generated by air sparging of HCl and NH_4OH solutions with interception of the gas streams at the inlet to the system. The particle generation rate was controlled by varying both the concentration of the solutions and the sparge air flow rate. The MgO and Na_2O particles were generated by metal vaporization and oxidation. The metal was heated inductively in an enclosed boat. An inert gas forced the metal vapors out the end of the tube where ignition to the oxide occurred. The generation rate was controlled principally by the temperature but also to a small degree by the inert gas flow. It was found that the aerodynamic mean diameter (AMD) was rather simply altered by varying the flow rate of the inert carrier gas. No special attempts were made to obtain a specific particle size or develop a technique for generating a monodisperse aerosol since this was not a specific part of the program. Since the technique was available for varying the particle size, some tests were made with MgO particles having an AMD of less than 0.1 μm.

An eight-stage Anderson sampler was inserted upstream of the charge section to obtain the aerodynamic mean diameter for each generation in which the conditions were altered. It should be recognized that the last stage of the available sampler had an effective cutoff diameter of about 0.4 μm for the isokinetic flow conditions. Since about 90 percent of the particle mass was collected on the filter, extrapolation of a log normal plot to obtain the AMD was a questionable practice although it was the only approach available at the time. Consequently, the stated AMD's are thought to be high. The apparent particle sizes and particle properties, shown in Table I, are the predominant observations for all generations. The mass median diameter (MMD) was calculated assuming a unit particle density and is related to the AMD by $MMD = \frac{AMD}{\sqrt{\rho}}$ where ρ is the particle density.

TABLE I

PARTICLE PROPERTIES OF GENERATED AEROSOLS

Particle	AMD in Microns	MMD in Microns	Resistivity in Ohm-Cm
NH_4Cl	0.25, 0.38	0.16-0.24	$\sim 10^8$
Na_2O	0.25, 0.3, 0.4, 0.6, 0.7	0.17-0.56	$\sim 10^{10}$
MgO	0.06, 0.1, 0.15, 0.25	0.03-0.13	$\sim 10^{12}$

SAMPLING

Mass samples were collected upstream of the corona charger and upstream and downstream of the fiber bed with the time increased as the rate of generation decreased. Millipore filters (0.65 μ pore size) were satisfactory for NH_4Cl and lower mass/unit-of-time generations for Na_2O and MgO. Fiber glass filters were required for the higher particle concentration tests of Na_2O and MgO to avoid changing the pressure drop across the calibrated flowmeters and to prevent sampling flow reduction or premature plugging of the filter.

The weight increase of the filter without particle generation, balance sensitivity (± 0.02 mg) and high filtration efficiency of the fiber bed prevented efficiency measurements at 50 ft/min face velocity and limited the maximum efficiency that could be determined at 100 ft/min to ~99.6 and ~99 percent for 100 mg/M^3 and 25 mg/M^3 concentrations without extensively increasing each test period. The weight gain of the filter was determined by sampling the tunnel air with charger on using double millipore filters. The top filter was tossed and the bottom filter weighed before and after desiccation at room temperature for up to four hours. The average weight gain was 0.02 mg and was not altered by drying in the desiccator. This suggested that bound moisture was creating the

weight bias. The fiber glass filters created an opposite problem since some sloughing off or loss of fibers generally resulted when removing the paper from the holder. This weight loss was reduced from about 0.15 mg to 0.04 mg by carefully brushing off the edges of the paper before weighing and inserting into the sampler. However, since these were used only for the higher flow rates at high air loadings, the fractional influence on the efficiency was around .002.

TEST PROCEDURE

The aerosol generator was started along with the elapsed generation timer and brought up to the desired generation rate as quickly as possible, the conditions for which had been previously, roughly established. Samples were collected at three points; namely, (1) upstream of the charger, (2) between the charger and bed and (3) downstream of the bed. The average volume flow rates and superficial bed velocities for any setting were based on the pitot tube profiles of the duct at the flow rates of interest. Velocity profiles at the three sampling points were not significantly different. Consequently, the same sampling flow rate was used for the three mass sampling points. The high particle and field charges at the second sampling point produced some odd results that defied interpretation and precluded the use of the data for determining the bed efficiency. For example, indicated bed efficiencies were 10 and 92 percent for two successive runs under identical conditions with both showing about 98 percent total efficiency. Consequently, the results reported are for the total efficiency of the system. More recent tests have shown a marked improvement in the comparative bed and system efficiencies -- within 1 to 2 percent with some being identical. The only change made to the system for these tests was an increase in the distance between the electrodes and ground rods of the charger which reduced the current to one-half of that observed with the original configuration. This further indicated the problem was associated with sampling in a high electrical field since a major reduction in the field downstream of the charger ameliorated the discrepancies markedly.

Generally, sampling was continuous until the end of the day or until apparent breakthrough (whichever came first) except during adjustment of generation rate and flow. Low aerosol concentration runs generally required two days of operation. When this occurred, the system was shut down over night. Prior to particle generation the second day, the charger was turned on to impose a field charge on the bed and a reentrainment test made at 300 ft/min flow. There were no apparent degrading effects even though the bed charge was at zero over night. For a series of measurements, the flow rate was varied from low to high and back to low or in the reverse order. Generally, two consecutive measurements were made before changing the flow and/or concentration.

It should be recognized that the collection efficiencies noted were based on mass measurements for submicron particles and comparative efficiencies would be expected to be higher for aerosols having a mass median diameter greater than 1 μm.

RESULTS AND DISCUSSION

With some modification of the spray-drop test system, most of its disadvantages encountered for submicron particulate studies were eliminated for the larger resuspended fly ash aerosol. The previous major problem of resuspended uncharged particles in the reducing transition duct between the charge section and the large verticle spray chamber was eliminated through a short coupling duct equal in diameter to that entering the charger. A few tests with submicron particulates were made following the revision to give more perspective to the original data and possibly indicate any test bed bias. These results are presented along with those obtained with the new wind tunnel system.

SPRAY-DROP SYSTEM TESTS

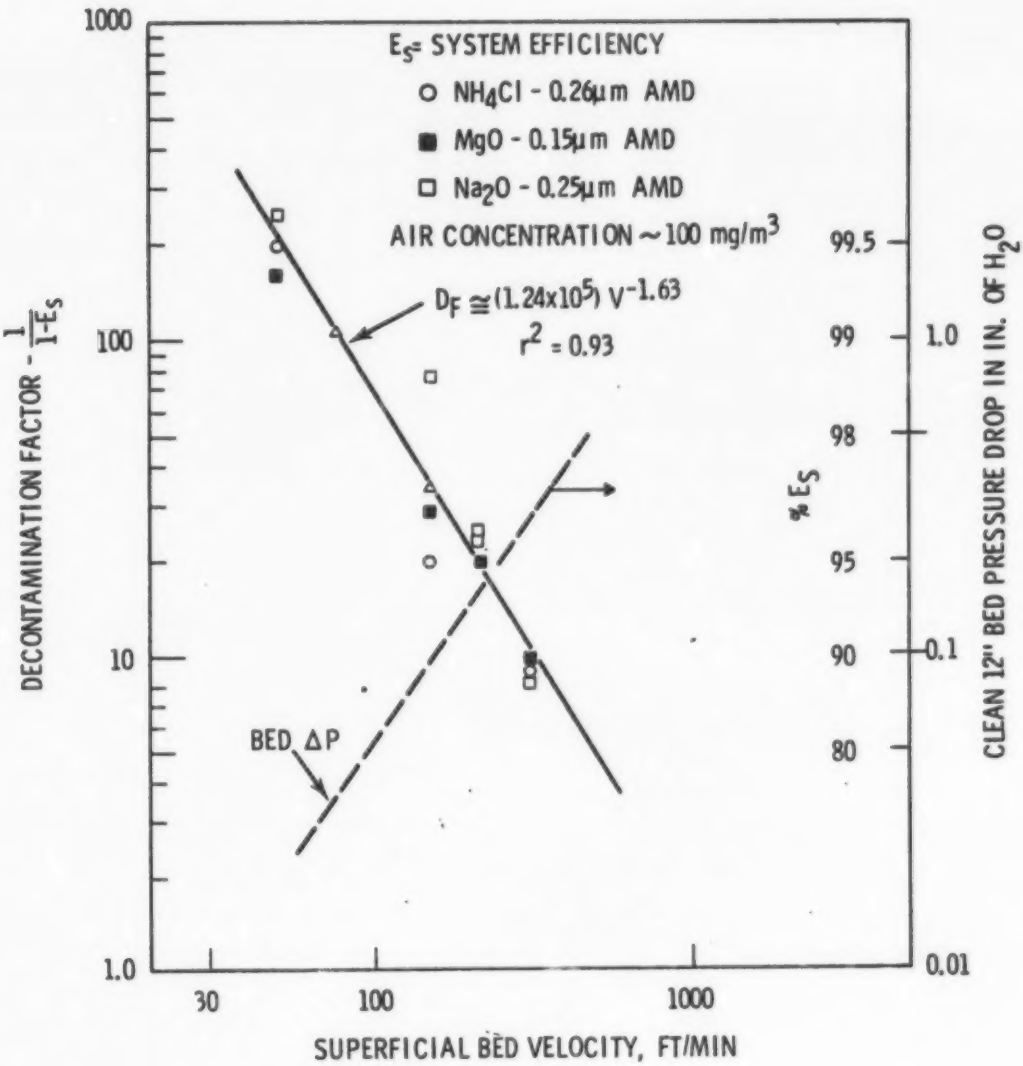
Bed Configuration

Since earlier work had shown predominent front face loading, the lower density 6 inch thick teflon demister [(VF) ∿0.975] was placed in front of the 6 inch thick polypropylene bed (VF ∿0.96) to form a 12 inch

thick bed of about 8 ft^2 area. From earlier visual observations the depth of particle penetration into the bed apparently was directly related to particle resistivity with the more highly resistive MgO depositing more uniformly throughout the bed depth than the NH_4Cl which was deposited predominantly in the first few inches of the lower void-fraction bed with Na_2O about intermediate between MgO and NH_4Cl. This somewhat graded fiber density altered the loading characteristics by producing a more uniform deposition throughout the first 8 inches of the bed without any apparent detrimental effects on efficiency. This extrapolates to a higher bed load for an equal pressure drop across the bed for the lower resistivity particles. For example, under similar NH_4Cl loadings, less than maximum, the 12 inch polypropylene bed of uniform fiber density showed an increase in pressure drop across the bed at 150 ft/min face velocity from 0.15 to 1.2 inches of H_2O while the teflon-polypropylene combination changed from $\sim$ 0.10 to 0.23 inches H_2O. In subsequent tests with the new system in which the loading was taken to breakthrough, an earlier breakthrough was observed for the MgO particles using the graded density configuration. This suggests that the use of a graded density bed might reduce the frequency of cleaning without any sacrifice in the efficiency if matched with the particle resistivity. Particle size may also exhibit a similar effect but was not observed over the particle size range tested - <1 μm.

System Efficiency for NH_4Cl, Na_2O and MgO

The system efficiency and aerosol decontamination factor for the three types of particles are shown in Figure 4. Comparison of this data with that previously generated showed that some of the inherent problems of the system were corrected by the revisions, especially at the higher flow rates where the efficiency was increased from about 75 to 90 percent at 310 ft/min flow. Also the linear relationship between velocity and efficiency was observed for the first time over the flow range of 50-300 ft/min. Some leakage along the bed frame was still observed particularly for the higher flow rates late in a run and probably accounts for some of the scatter in the data as well as a lower indicated efficiency.



DECONTAMINATION FACTOR - 12" FIBER BED
OLD SYSTEM

FIGURE 4.

As would be expected, the log of the decontamination factor varied linearly with a power of the velocity. Since there was no apparent distinguishing trend with respect to particle resistivity or size, the data were considered as from a single population for the least squares fit, shown by the curve, which showed relatively good agreement with a correlation coefficient of 0.93. The pressure drop shown in Figure 4 is for a clean bed. For these tests the pressure drop increase at the end of each series of measurements averaged about 20 percent.

The equations for the least squares fit of the data for each particle are shown in Table II along with the coefficient of determination.

TABLE II

Emperical Equations of Efficiency

12" Thick Bed - Spray-Drop Test System

Particle	Equation	r^2
NH_4Cl	$E_S = 101.05-0.041V$	0.996
Na_2O	$E_S = 100.96-0.02V$	0.85
MgO	$E_S = 101.68-0.035V$	0.96

E_S = System Efficiency

V = Bed Superficial Velocity - ft/min.

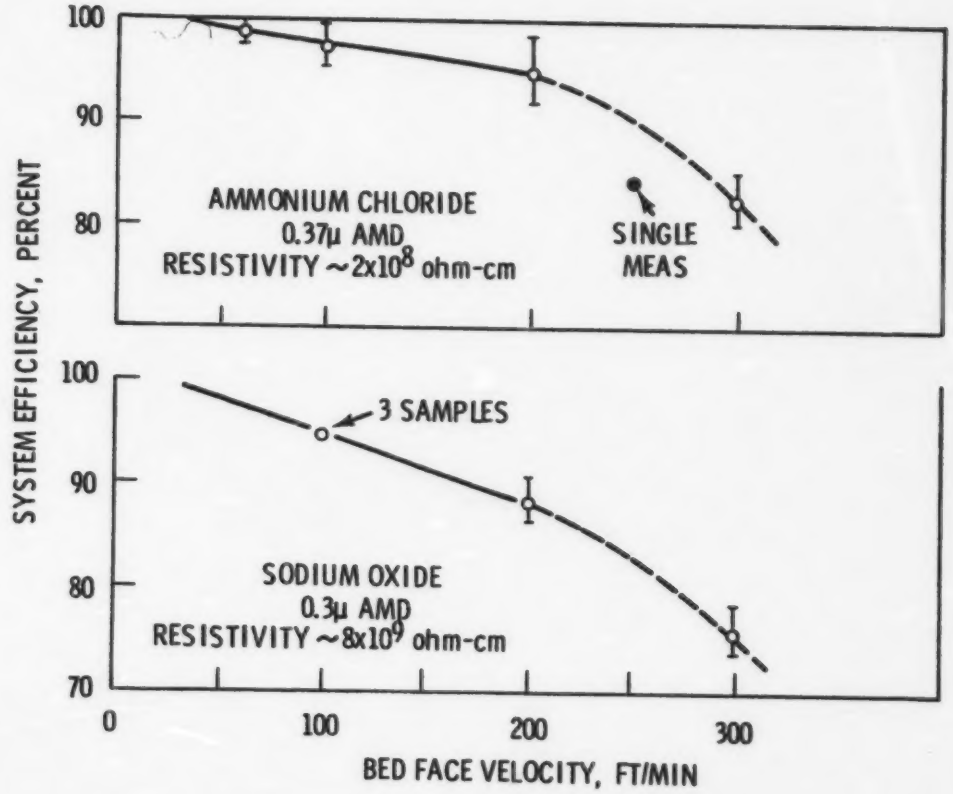
The poor correlation coefficient for Na_2O reflects the low efficiency obtained at 310 ft/min face velocity ascribed to the high leakage along the frame.

NEW WIND TUNNEL TESTS

Polypropylene Bed - Six Inch Thick

The void fraction for this bed was approximately 0.96. Figure 5 shows the average efficiency as a function of velocity as well as the sample 2σ limits. For both, the efficiency up to 200 ft/min filter face velocity is approximately linear and then appears to change to some other function or to a linear function with a different slope. Sufficient data are not available to describe the point of change and/or any change in the relationship between 200-300 ft/min. The single NH_4Cl measurement at 250 ft/min was the last measurement taken before bed cleaning and is thought to be low due to observed breakthrough which, from visual observation, was assigned to migration of the particles along the lucite frame. This short circuiting was observed only after the pressure drop increase in the original flow regime of the bed diverted some of the flow to the outer edges. The supporting wire grid work appeared to accentuate the diversion of particles to the bed fringes as evidenced by the predominant earlier particle migration along the wires. This leakage along the bed frame would be eliminated with a fiber bed designed for this specific application. The equations developed from a linear regression fit of the data, 200 ft/min velocity and below, are shown in Table III and represented by the solid line in Figure 5.

The total efficiency measured for Na_2O was significantly lower than that for NH_4Cl which has a lower resistivity than Na_2O. Since this was contradictory to the developed theory which predicts a decreasing efficiency with decreasing particle resistivity due to a lower space charge, an investigation was initiated to shed some light on the observation. During examination of all operating data it was noted that the current flow in the charger during this series of measurements increased with time and was uncharacteristically very high during the last few measurements at 200 and 300 ft/min. Examination of the charging section showed that a buildup of Na_2O on the terminal weights of the



SYSTEM EFFICIENCY VS FLOWRATE
6" POLYPROPYLENE BED
0.96 VOID FRACTION

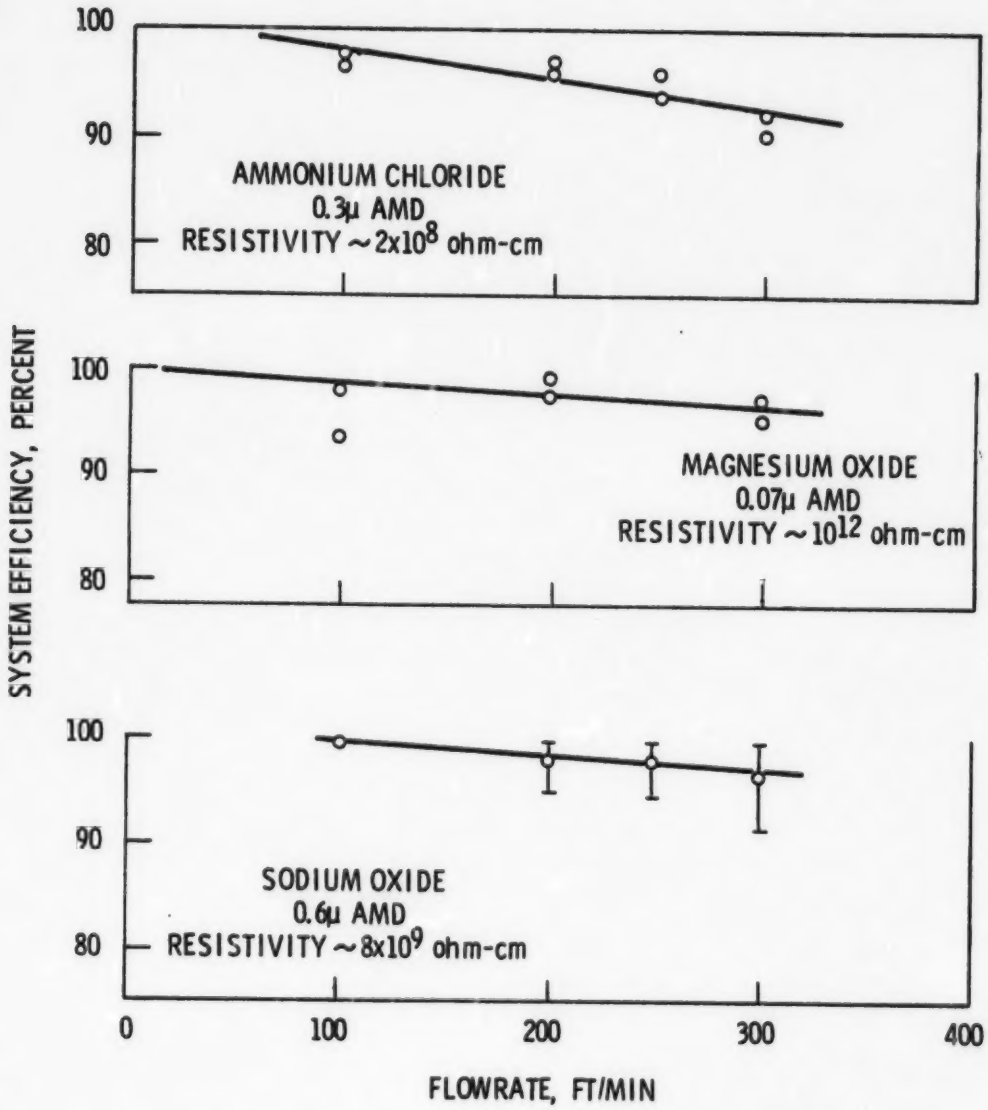
FIGURE 5.

electrodes, which were nearly touching the ground rods, created a more conductive path to ground through absorption of moisture and subsequent formation of the more conducting NaOH. Thus this effectively reduced the corona field and apparently the particle charging efficiency resulting in an anomalously low system efficiency at least near the end of the series. Another indicator of this problem was the necessity to reduce the power supply voltage gradually with time to prevent automatic cutoff by the power supply current limit switch. The moral of this sequel is to never use Na_2O test aerosols at high air humidity (> 40 percent) when the electrode weights are in close proximity to an electrical ground that produces a direct short -- principally a geometric design problem.

Twelve-Inch Thick Polypropylene Filters

The first six inches of this bed were packed to a void fraction of 0.975 with the last six inches at $\sim$ 0.96 principally to extend the run time for NH_4Cl aerosols of the higher concentrations. Since there was no discernable effect of particle concentration on system efficiency over the range of 6-148 mg/M^3, only higher concentrations were used in this series of tests in an effort to reduce the run time and maintain reasonable reproducibility. This was accomplished to some degree but again sensitivity of the measurements produced a higher variability than desired. However, the frequency of unexplained "fliers" was significantly lower.

The efficiency for NH_4Cl, MgO and Na_2O is plotted against flow rate in Figure 6. As shown by the least squares fit curves, the efficiency decreased linearly with increasing velocity at least up to 300 ft/min flow rate. The Na_2O data points are the average of all measurements at a single velocity. The 95 percent confidence limits are also shown. The MgO and NH_4Cl data are duplicate measurements. Consequently, all data are plotted and no limits shown. The low point at 100 ft/min for MgO appears to be one of those "fliers" that occur now and then without any apparent explainable reason. However, with a statistically significant number of tests, these generally fall out as "outliers". Consequently, it was not used in the linear regression analysis. Although



SYSTEM EFFICIENCY VS FLOWRATE
12" THICK POLYPROPYLENE
GRADED BED VOID FRACTION

FIGURE 6.

this value was not used, the data indicate an efficiency less than 100 percent at zero flow -- not very probable. This suggested that these last two measurements at 100 ft/min (∿ 50 cms/sec) in the run series flow were probably on the low side due to edge leakage.

The average efficiency for NH_4Cl was lower than that of MgO or Na_2O by about 2 to 5 percent over the range of 100-300 ft/min face velocity. This is the first data that might confirm the model's prediction that efficiency should decrease with decreasing resistivity. Since the bulk of the data does not indicate a like trend, final judgment is reserved until a statistically significant number of measurements are completed. Also bearing on the reservation is the lack of any discernable difference in the bed field charge, inferred from current measurements, between the three aerosols used. Thus, it is not unlikely that significantly lower efficiencies would be observed only for a much more conducting particle and the threshold for this effect would occur at a lower resistivity than the 10^8 ohm-cm of NH_4Cl. The linear equations for the lines, Figure 6, are shown in Table III.

TABLE III

Emperical Equations of Efficiency

Particle	6" Bed - < 200 ft/min	12" Bed - < 300 ft/min
Na_2O	E = 101.5 - 0.065V	E = 100.91 - 0.0116V
Mgo		E = 99.8 - 0.0116V
NH_4Cl	E = 100.513 - 0.028V	E = 101.286 - 0.0283V

Where E = Efficiency in Percent and,
V = Superficial Bed Velocity - ft/min.

Aerosol Decontamination Factor

The calculated decontamination factors for both the six inch and twelve inch beds are plotted as a function of velocity in Figure 7. The data approximate the expected relationship with the log of the decontamination factory varying linearly with the power of the velocity. For the six inch bed, all data were considered to be from the same population for the least squares fit which is represented by the solid line. This appears to be a reasonable assumption since the coefficient of determination was 0.9 and all data fell within the 2σ limits of sampling and measurement errors. Consequently, the fitted equation probably represents a reasonable average for the experimental conditions.

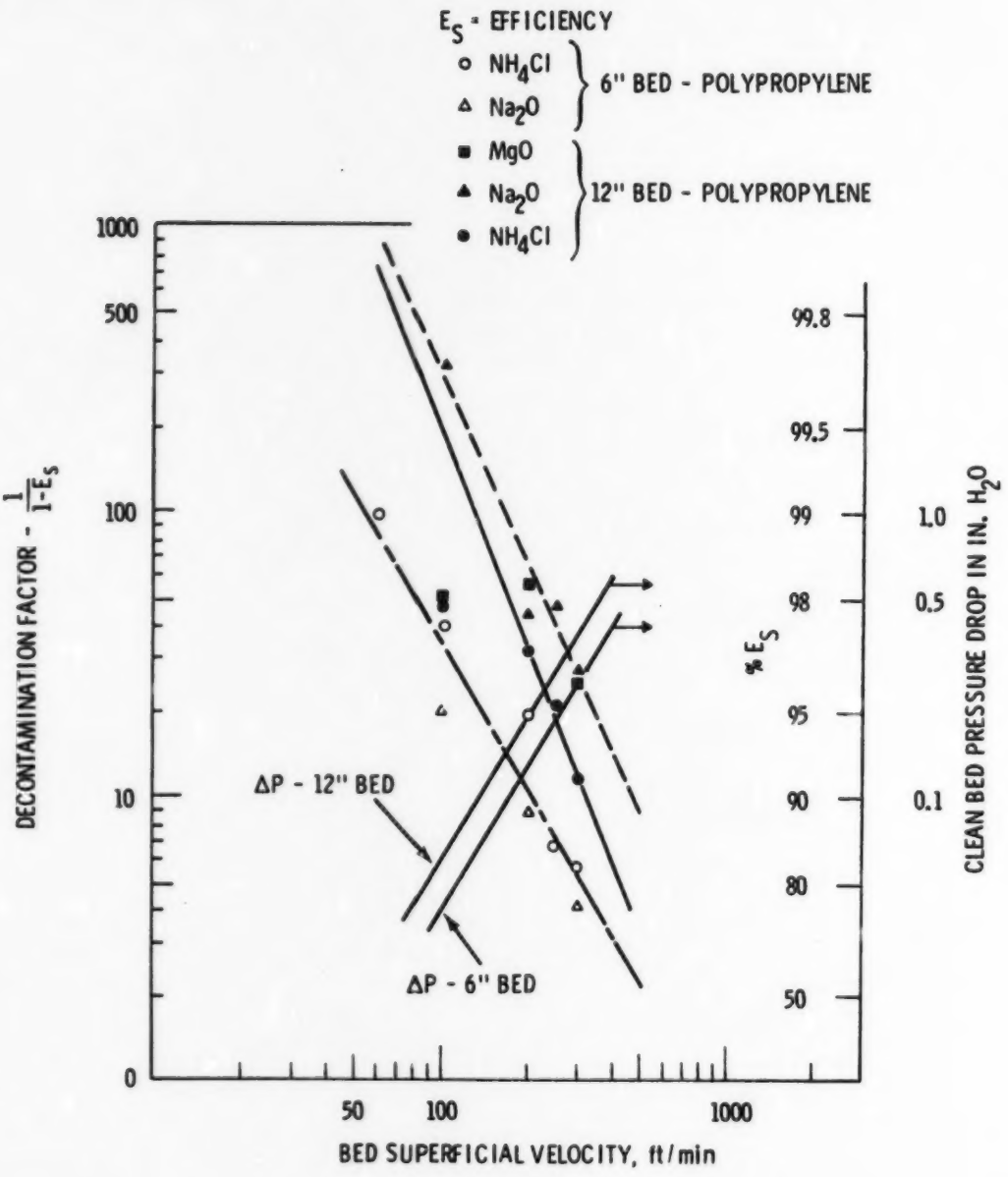
For the twelve inch bed, the log-log plot of the data suggests a real, although small, difference in the bed efficiency for NH_4Cl particles compared to that for Na_2O and MgO and were segregated for calculation of the linear regression fit of the data while the Na_2O and MgO data were lumped together. The apparently anomalously low values for NH_4Cl and MgO (100 ft/min - 50 cms/sec) were the last samples taken in each series when the operating log noted leakage along the bed edges. Since it is unrealistic, based on the preponderance of data, that the efficiency should decrease with decreasing velocity, the bed leakage was assigned as the major cause for the low values which were not included in the curve fitting process. The pressure drop curves shown in Figure 7 are for the previously described void fractions in a clean state. The equations for the fitted curves are contained in Table IV.

TABLE IV

Decontamination Factor Empirical Equations

(New Wind Tunnel)

Fiber Bed	Partical Type	Partical Size	
Six Inch V.F. - 0.956	NH_4Cl	~ 0.3	$D_f \cong (9.5\times10^4)V^{-1.72}$, $r^2 = 0.9$
	Na_2O	~ 0.25	
Twelve Inch V.F. - 6" at 0.975 and 6" at 0.956	NH_4Cl	~ 0.25	$D_f \cong (2.12\times10^7)V^{-2.52}$, $r^2 = 0.99$
	MgO	~ 0.06	$D_f \cong (7.8\times10^6)V^{-2.21}$, $r^2 = 0.97$
	Na_2O	~ 0.25	



FIBER BED DECONTAMINATION FACTORS

FIGURE 7.

Three-Inch Thick Fiber Bed

Since the efficiency appeared to be dependent upon fiber density as well as the demonstrated dependence on thickness, a run series was made with the NH_4Cl aerosol using a three inch thick bed packed to a void fraction of 0.946. In this test series it was planned to obtain successive measurements at one velocity until breakthrough at the bed edges was apparent. In an effort to increase the number of consecutive measurements at the high aerosol concentrations used, a folded fiber mat was inserted at the bed-frame interface to bring the fiber density at that point nearer to that in the rest of the bed. This produced a marked improvement in total run time before edge breakthrough was indicated at a much higher pressure drop than in previous tests. Under normal industrial applications, cleaning of the bed would precede the more than an order of magnitude increase in the bed ΔP observed in the lab tests. Five successive measurements were made for all flowrates except 100 ft/min where 20 measurements were made. The particle size for this series of tests hovered around 0.25 μm AMD at a mass concentration near 75 mg/M^3.

The equation developed from the least squares fit of the efficiency versus velocity was

$$E_S = 102.8 - 0.0514\ V$$

where

E_S = system efficiency in percent and,

V = bed face velocity in ft/min and

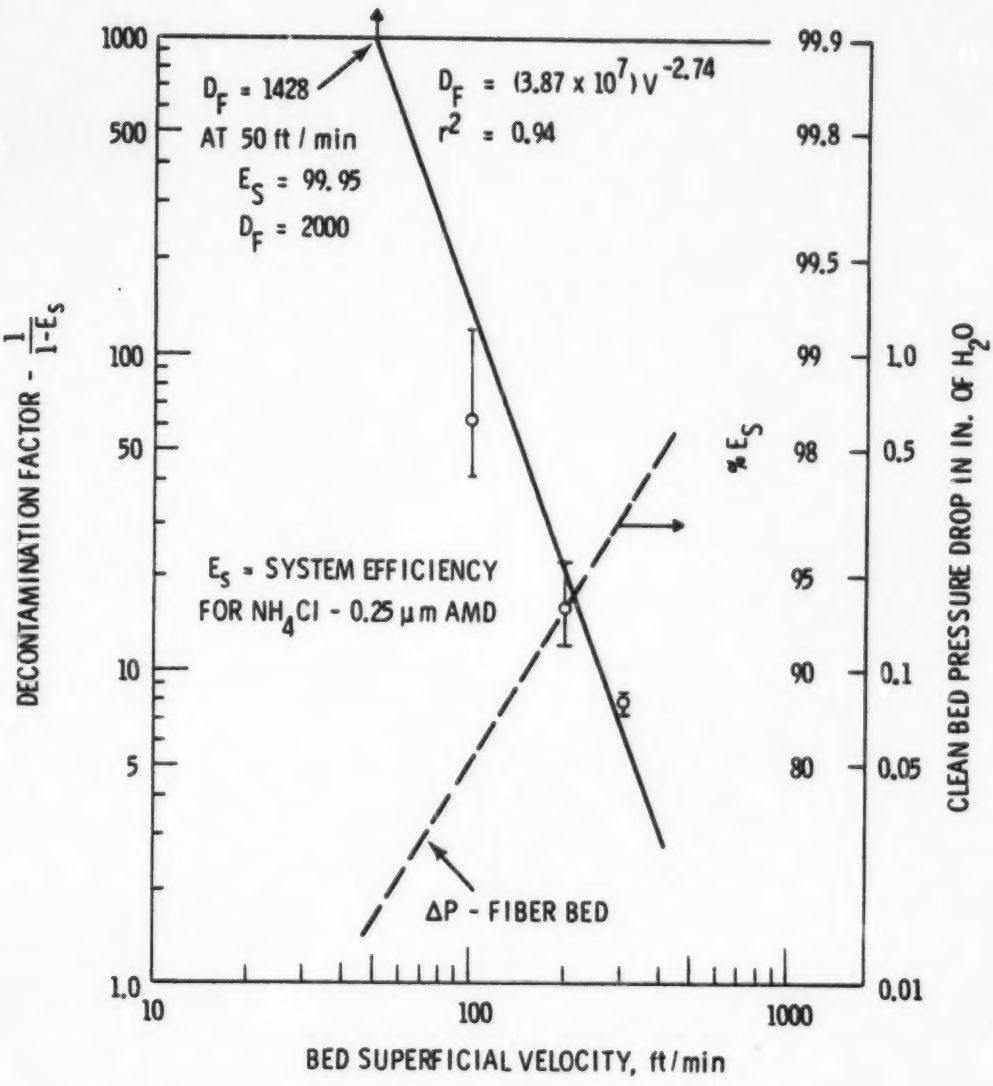
$r^2 = 0.986$.

The plot of the decontamination factor vs. velocity (Figure 8) shows the average values for each velocity along with the 95 percent confidence levels. The equation developed from the least squares fit was

$$D_f \simeq (3.87 \times 10^7)\ V^{-2.74}$$

where

$D_f = \frac{1}{1-E_S}$, dimensionless and



DECONTAMINATION FACTOR FOR FIBER BED
3 INCH POLYPROPYLENE - 0.946 VOID FRACTION

FIGURE 8.

V = bed face velocity in ft/min and,

$r^2 = 0.94$

The slope of the regression line was highly influenced by the D_f of 2000 at 50 ft/min face velocity. The relatively poor fit suggests either that the sensitivity of the measurements was insufficient to accurately determine the efficiency at the lowest velocity giving a high value or that the log of the decontamination factor is not linearly related to a power of the velocity at lower flowrates. Thus similar tests at several velocities between 25 and 100 ft/min will be required to describe the relationship. However, some measurement method other than mass will be required to provide adequate sensitivity at the sampling point downstream of the bed at these lower velocities.

Comparatively, this thinner 3 in. bed with a lower void fraction exhibited an efficiency about equal to the 6 and 12 in. beds at 100 ft/min flow rate and was about 5 percent higher and lower than the 6 and 12 in. beds at 300 ft/min flow rate. At 50 ft/min, measurements indicated a 100 percent efficiency for the first six hours of continuous operation. The initial pressure drop across this bed was slightly higher and lower than the 6 and 12 in. beds.

This test illustrates that for low flow rates and low aerosol load the thinner bed would have a practical application. The dependency of efficiency on both the fiber bed thickness and density was demonstrated but not in sufficient detail to develop a mathematical relationship.

Six-Inch Thick Stainless Steel Bed

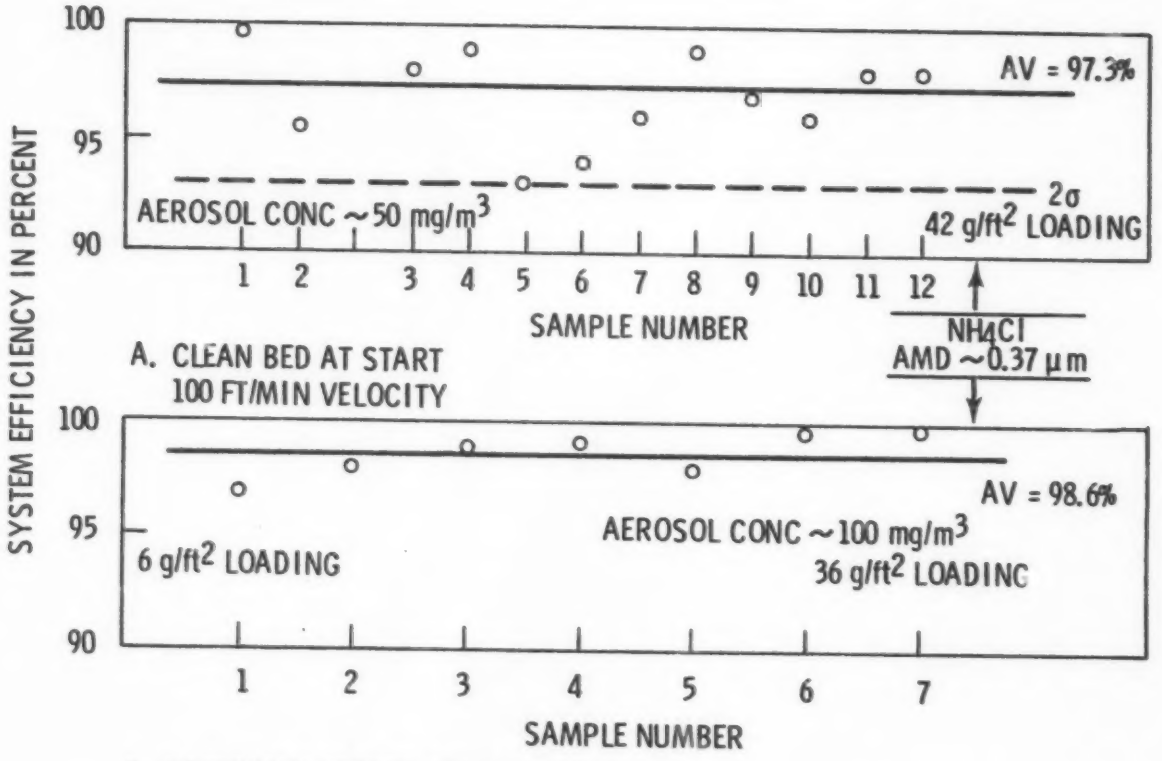
The series of experiments preceding the discovery of this concept suggested that an electrically non-conducting fiber bed was required to obtain the observed high collection efficiencies. To support this idea, a conducting bed of stainless steel was tested under equivalent conditions. As suspected, the efficiencies obtained were very low, between 35 and 43 percent at 350 and 50 ft/min face velocity, compared to the 18 and 35 percent calculated for image force collection under the test conditions. The higher conductivity of this bed results in charge leakage at a much lower charge level on the bed and illustrates the importance of the level of field charge developed in "non-conducting" the bed.

Bed Loading Runs

Data collected during two NH_4Cl loading runs at 100 ft/min face velocity are shown in Figure 9A for a clean bed at the start of the run and Figure 9B which started with a partially loaded bed from the previous days' tests. Obviously, the scatter in the data was greater at 50 mg/M^3 aerosol concentration than at twice that concentration. As discussed previously, this scatter in the data was ascribed to the sensitivity of the mass measurement for the downstream sampling position which was hovering around the balance sensitivity at these high efficiencies and aerosol concentrations. Although the averages of the efficiencies appear to be different, it is thought to be principally an artifact of the sensitivity rather than a real difference since differences in the efficiency due to aerosol concentration over the range tested were not discernable. There appears to be a slight trend for the efficiency to increase with bed loading, Figure 9B, which was also observed with other loading runs made at a constant velocity.

Pressure Drop Increase

The increase in pressure drop with bed loading appears to be predominantly a function of both the bed void fraction and particle characteristics which apparently influence the predominant plane of deposition perpendicular to the flow at least for the submicron size range. The aerosols of 2 μm AMD size and above may also influence depth of penetration into the bed. The velocity of air flow might also be a factor in directing the depth of penetration but cursory visual observations indicate that it would be of a second order magnitude. This later impression was obtained from the NH_4Cl aerosols over a flow range of 50-300 ft/min. For these tests visual inspection did not reveal any dramatic change in the plane of principal deposition which would have been required to be discernable. This is also supported to a degree by the much faster pressure drop increase for the higher flow rates under equal aerosol concentrations. Specific tests to define the effect of velocity on the pressure drop-bed loading relationship have not been made. Relative comparisons, for a bed void fraction of 0.96, 100 ft/min face velocity and an approximately equal pressure drop increase from 0.08 to 0.3 in. of H_2O, gave bed



EFFICIENCY VS LOADING - 6" BED
0.96 VOID FRACTION

FIGURE 9.

loadings of about 540, 650 and 970 g/M^2 for approximately 10^8, 10^{10} and 10^{12} ohm-cm particle resistivities having nearly equal AMD's.

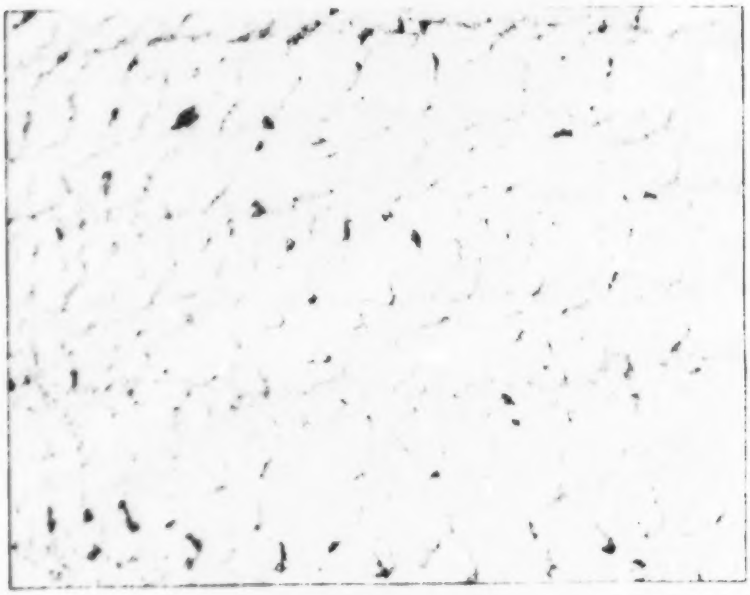
For non-characteristic aerosols, like the ones used, any tests defining the load - ΔP - VF relationship would be of academic interest only. The information obtained to date suggests that for industrial applications, particle characteristics, principally resistivity and concentration and secondarily size as well as the control system operating conditions are necessary to optimize the efficiency, cleaning frequency and area of the fiber bed.

Pictures of a loaded bed, Figure 10, show the upstream and downstream faces of a fiber bed loaded with NH_4Cl particles. The pictures are somewhat deceiving since the front face gives the appearance of being plugged. However, the pressure drop across this 12 in. thick bed under this particle load of ~80 g/ft^2 was about 0.9 in. of water at 300 ft/min face velocity. Although not readily visible, there was a very slight deposit on the rear face fibers and support wires.

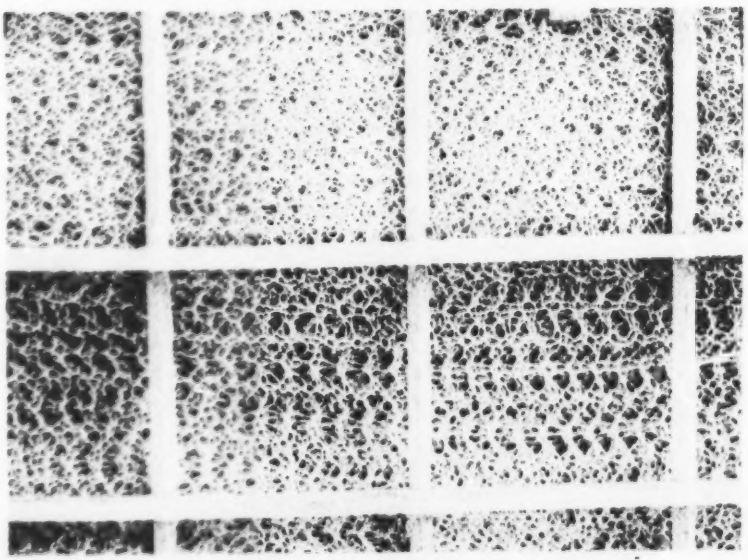
Electrical Properties of Bed

The electrical properties of the bed could only be inferred from the leakage current of the bed and from the screens positioned as shown in Figure 3. The bed leakage current was obtained from a bare wire encompassing the bed at the frame-bed interface. A single wire was found to produce the same leakage current as a full width aluminum foil. From the measured leakage current of the bed and the four screens, the space charge of the bed built instantaneously upon activation of the charger to about a factor of ten less than that observed during particle generation and increased proportionally with flow rate. This suggests that molecular ion or charged Aitken nuclei deposition produces a significant contribution to the bed field charge and deposition of charged particles is not required to initiate the collective action. The charge varied with mass per unit time depositing on the filter but only by about a factor of five over the range tested (10-150 mg/M^3). At any one particle deposition rate the space charge increased immediately by an order of magnitude and then remained constant indicating that charge leakage from the bed was equal to that deposited with the particles.

LOADED POLYPROPYLENE FIBER BED
12 INCH THICK
VOID FRACTION ~0.96
NH_4Cl PARTICLES - 0.25μm AMD
LOAD ABOUT 150 g/ft^2



UPSTREAM FACE



DOWNSTREAM FACE

By assuming that the charge distribution in the bed is directly proportional to current measurement, some inferences relative to its shape can be made from the current measurements of the planted screens. For the 6 in. bed, there is an order of magnitude decrease between the front and rear face which prevailed throughout the run and was present with or without particle deposition. This suggests essentially an instantaneous distribution of the charge deposited by the particles. The field charge distribution transverse to the flow appeared to be uniform within the rather approximate measurements resulting from the fluctuating meter. The above observations prevailed also for the 12 in. thick bed except the average reduction in the inferred field charge front to rear was about 20 and was more variable than for the 6 in. bed.

CONVERSION FACTORS

To Convert	To	Multiply By
feet/minute	centimeters/second	5.08×10^{-1}
inches	centimeters	2.54
inches of H_2O	atmospheres	3.34×10^{-2}